Time varying gravity from SLR and combined SLR and high-low satellite-to-satellite tracking data

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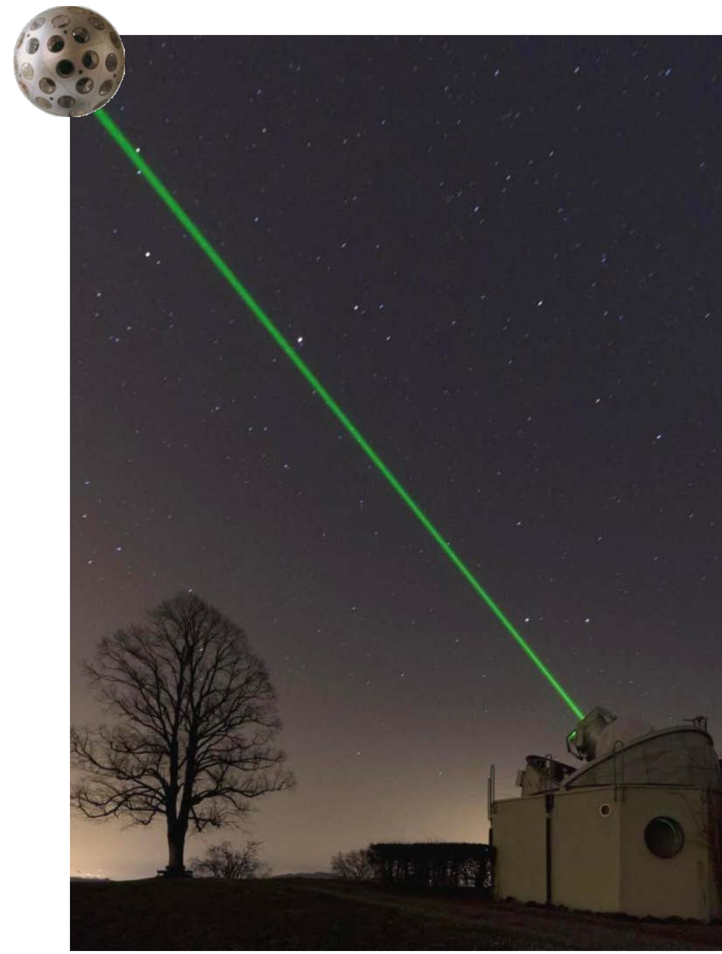
ITSG

Satellite Laser Ranging (SLR)

- SLR provides very precise (at a few mm-level) distance measurements between ground stations and satellites.
- SLR geodetic satellites have minimized area-to-mass ratios. They orbit the Earth at higher altitudes than the satellite missions dedicated to gravity recovery.
- Up to now SLR observations were mostly used for deriving low-degree gravity field coefficients (mainly degree 2) or zonal harmonics.
- We show that also tesseral and sectorial harmonics up to d/o 10/10 of monthly gravity field models can be very well derived from SLR observations.

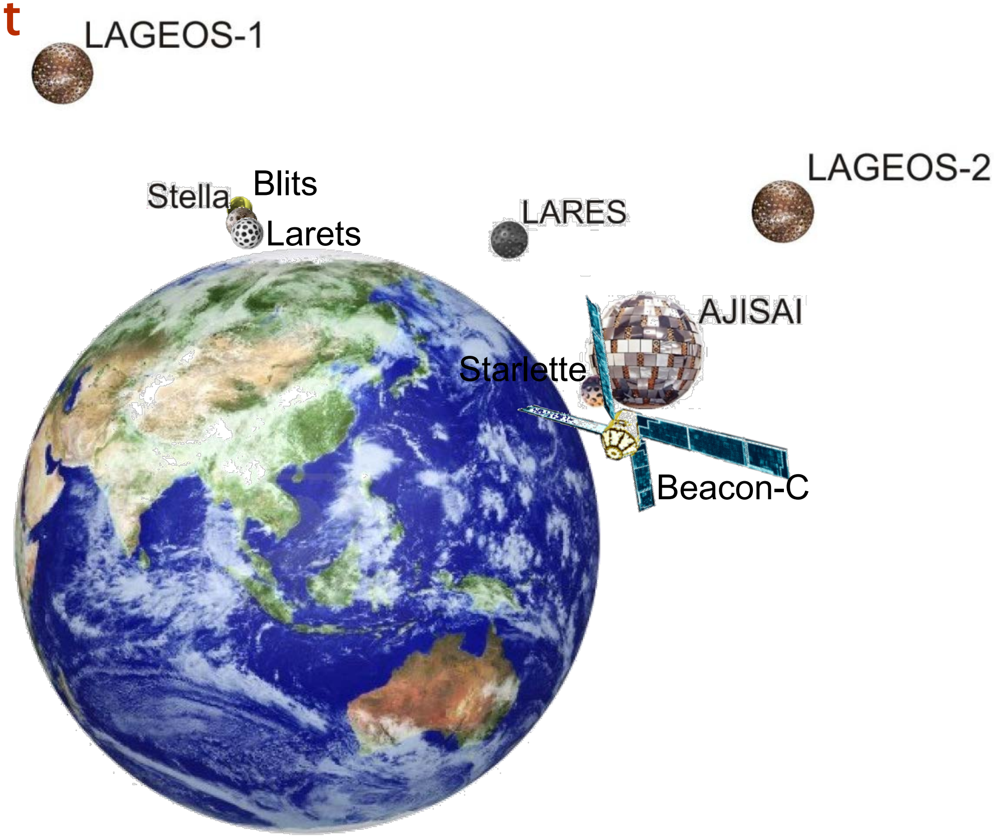


SLR station in Zimmerwald, Switzerland

SLR-only solutions

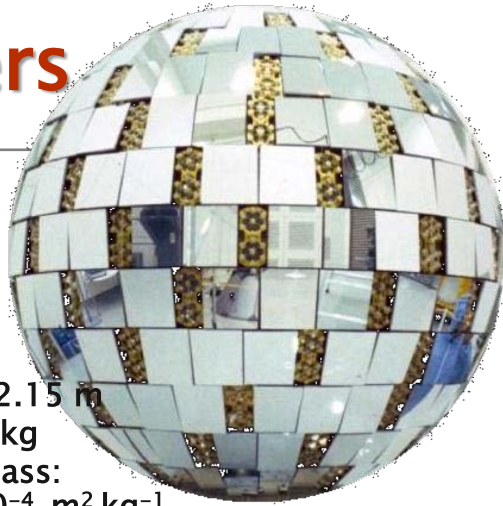
Space Segment of SLR satellites

- Up to 9 SLR satellites with different altitudes and different inclinations are used.
- For LAGEOS-1/2 10-day arcs are generated without estimating once-per-revolution empirical accelerations in out-of-plane (due to correlations with C_{20}).
- For low orbiting satellites 1-day arcs are generated.
- Different weighting of observations is applied: from 8mm for LAGEOS-1/2 to 50mm for Beacon-C.



List of estimated parameters

Estimated parameters		SLR solutions: LAGEOS-1/2, Starlette, Stella, AJISAI, LARES, Blits, Larets, Beacon-C
Orbits	Osculating elements	a, e, i, Ω, ω, u_0 (LAGEOS: 1 set per 10 days, LEO: 1 set per 1 day)
Orbits	Dynamical parameters	LAGEOS-1/2 : S_0, S_S, S_C (1 set per 10 days) Sta/Ste/AJI : C_D, S_C, S_S, W_C, W_S (1 set per day)
Orbits	Pseudo-stochastic pulses	LAGEOS-1/2 : no pulses Sta/Ste/AJI : once-per-revolution in along-track only
Earth rotation parameters		X_P, Y_P, UT1-UTC (Piecewise linear, 1 set per day)
Geocenter coordinates		1 set per 30 days
Earth gravity field		**Estimated up to d/o 10/10** (1 set per 30 days)
Station coordinates		1 set per 30 days
Other parameters		Range biases for all stations (LEO) and for selected stations (LAGEOS)



AJISAI :

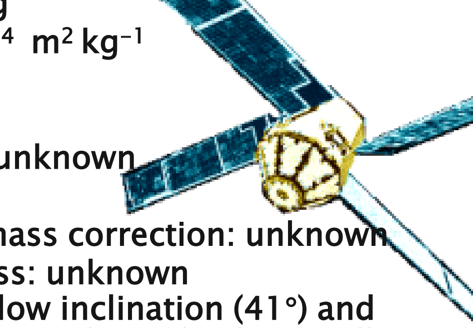
- Diameter: 2.15 m
- Mass: 685 kg
- Area-to-mass: A/m: $58 \cdot 10^{-4}$ $m^2\,kg^{-1}$

LAGEOS :

- Diameter: 0.60 m
- Mass: 407 kg
- A/m: $6.9 \cdot 10^{-4}$ $m^2\,kg^{-1}$

LARES :

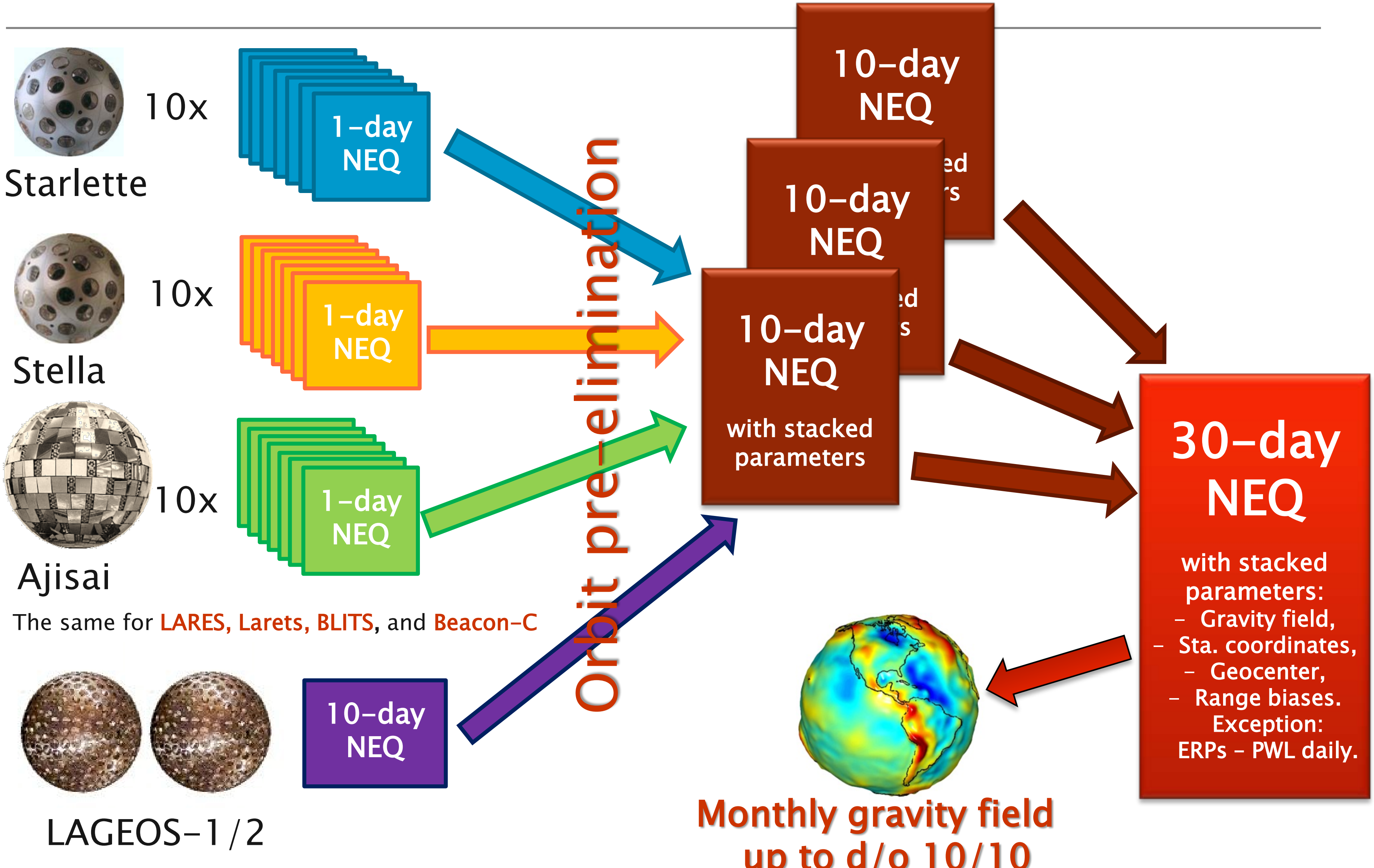
- Diameter: 0.36 m
- Mass: 387 kg
- A/m: $2.7 \cdot 10^{-4}$ $m^2\,kg^{-1}$



Beacon-C:

- Dimension: unknown
- Mass: 32 kg
- Center-of-mass correction: unknown
- Area-to-mass: unknown
  BUT: due to low inclination (41°) and large eccentricity (0.023) , this satellite can be used for decorrelation of some gravity field parameters.

Processing scheme



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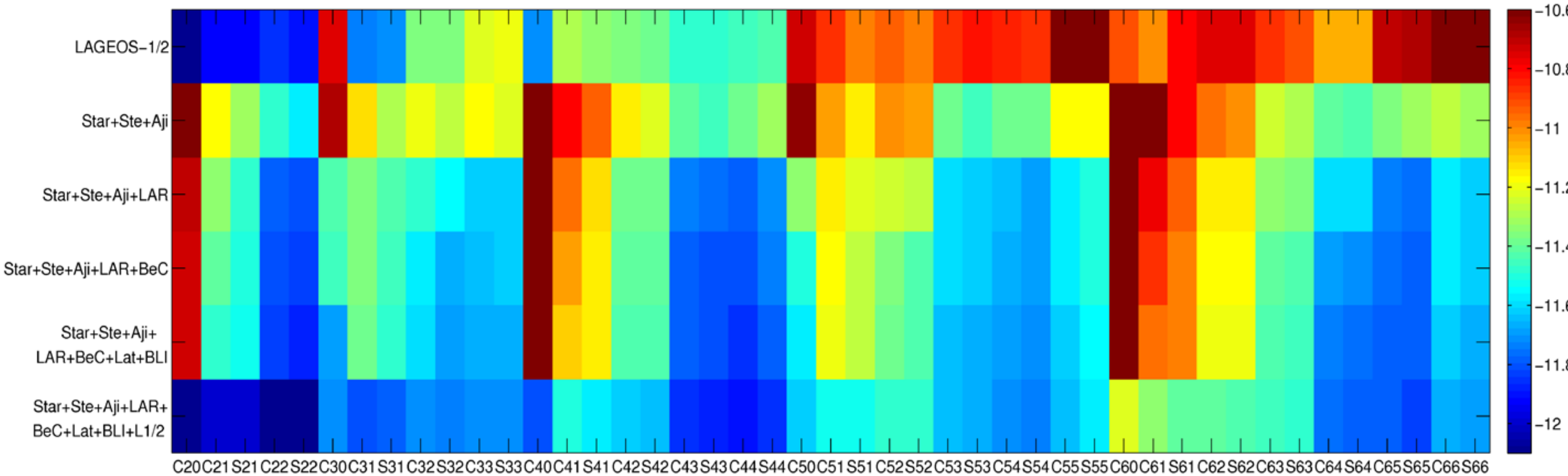
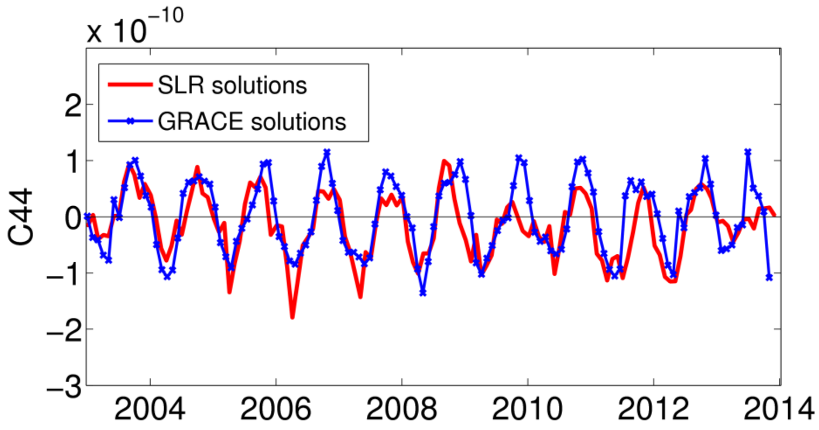
Sensitivity of SLR satellites to SH coefficients



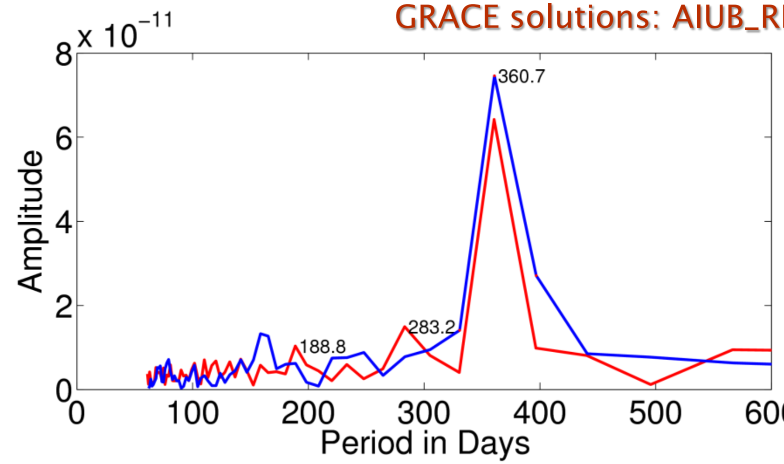
Formal errors of coefficients up to d/o 6/6 in log scale

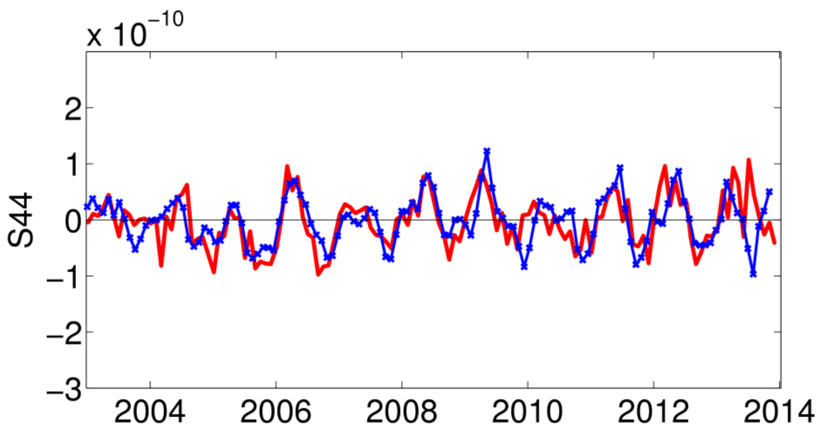
- LAGEOS-1/2 are very sensitive to degree 2 SH.
- LAGEOS sensitivity drops down for degrees higher than 4.
- LEOs are not very sensitive to even zonal coefficients (C20, C40, C60) due to short arcs (1-day) and estimated empirical orbit parameters.
- LARES remarkably contributes to degree 4 and 6.
- Contribution from Larets and Blits is small.

Comparison w.r.t. GRACE K-Band

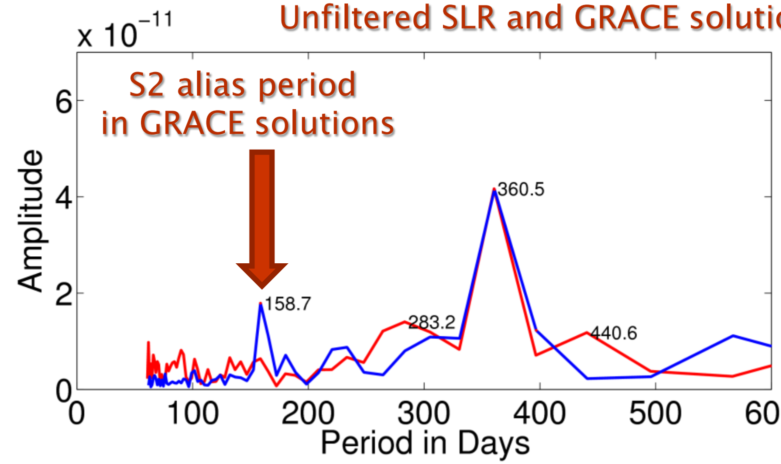


GRACE solutions: AIUB_RL02





Unfiltered SLR and GRACE solutions



SLR and GRACE solutions agree very well, especially for sectorial and tesseral SH coefficients.

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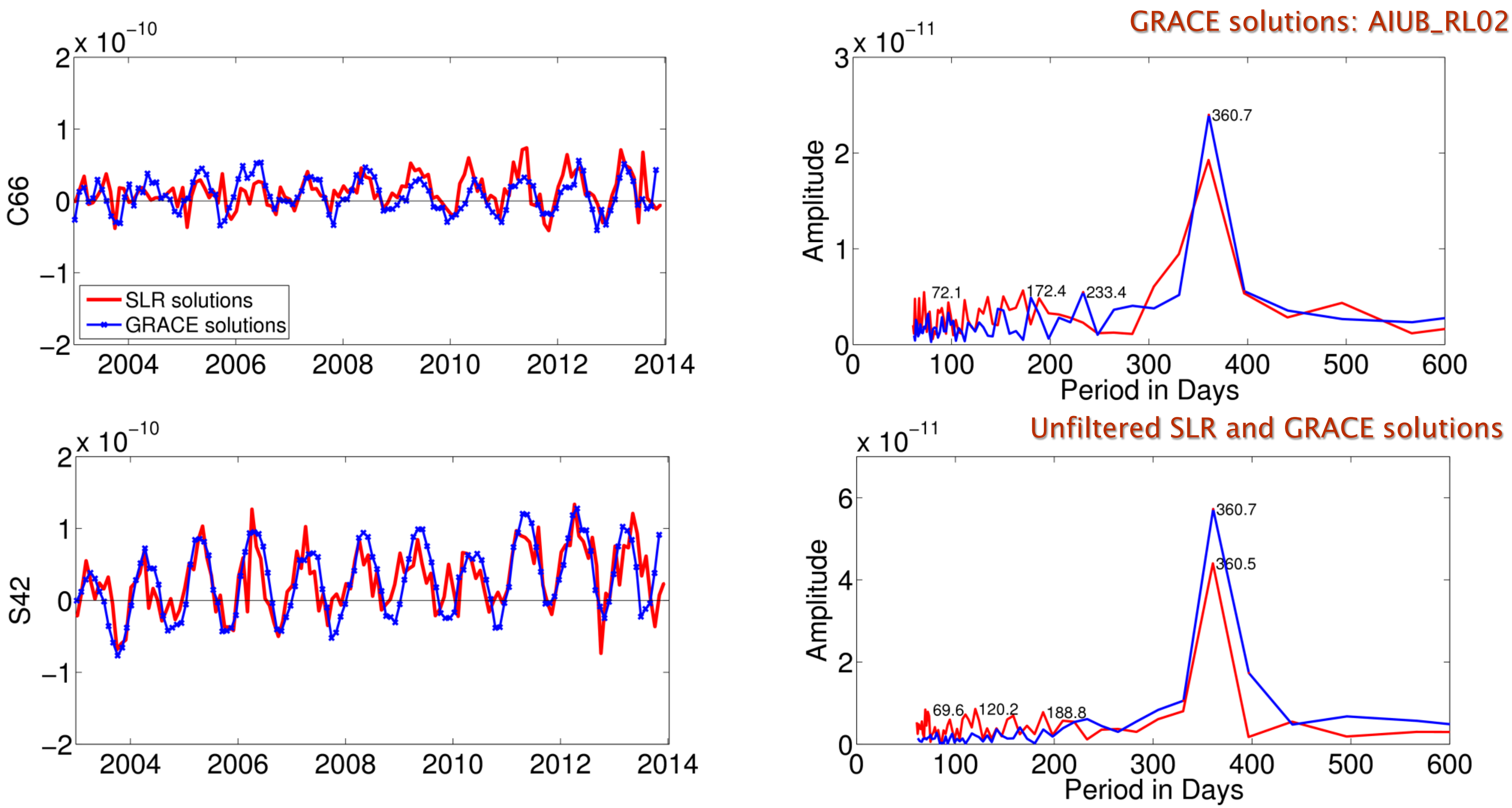
Comparison w.r.t. GRACE K-Band



Even the coefficients of degree 6 can be still very well recovered by SLR.

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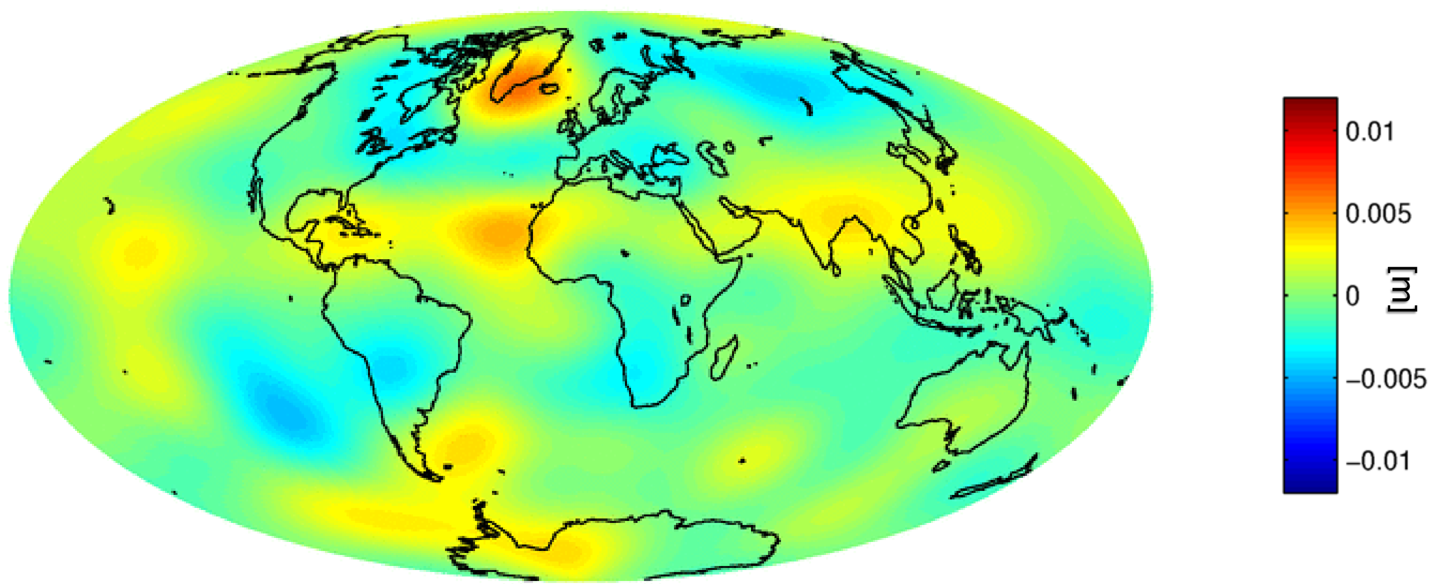
SLR-only solutions

SLR can recover the largest gravity variations, e.g., in Amazon basin, Greenland, Africa, and South-East Asia. The spatial resolution is, however, limited due to high satellite latitudes and a low number of data.



Mean monthly gravity field variations up to d/o 10/10 derived from SLR-only (no filtering applied, scale in m)

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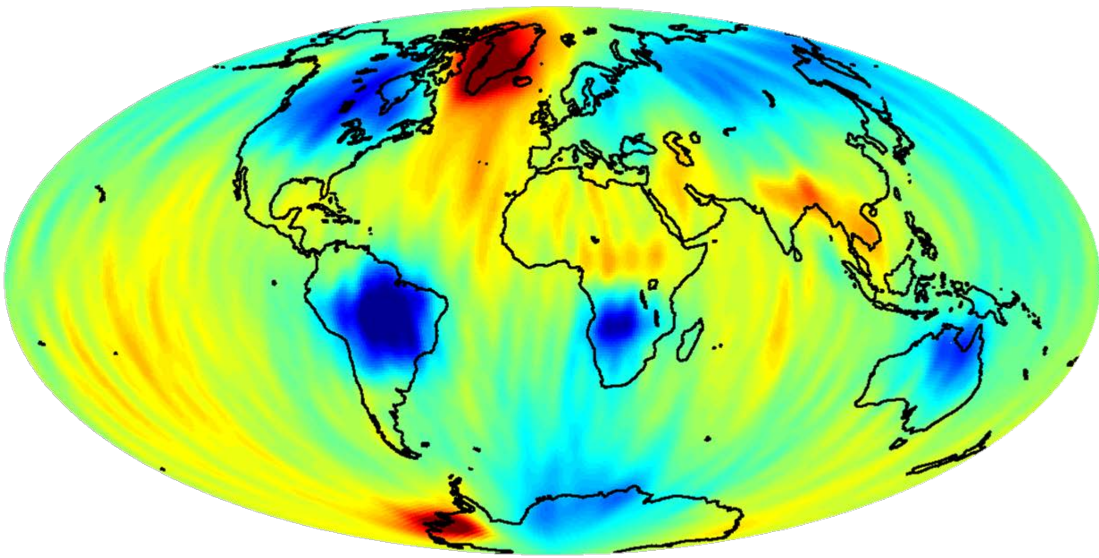
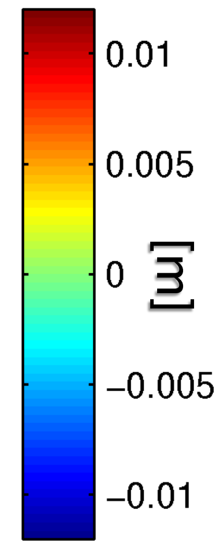
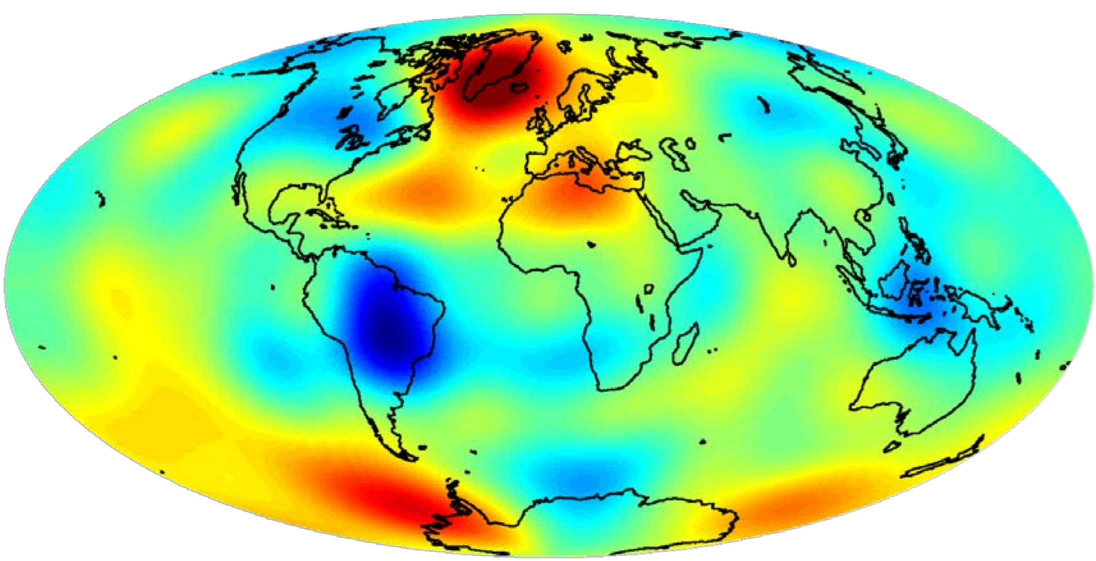
SLR-only solutions



GRACE K-band solution
AIUB-RL02,
March 2011,
up to d/o 60/60
filtering 300 km





SLR-only solution,
March 2011,
up to d/o 10/10
no filtering

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SLR-only solutions

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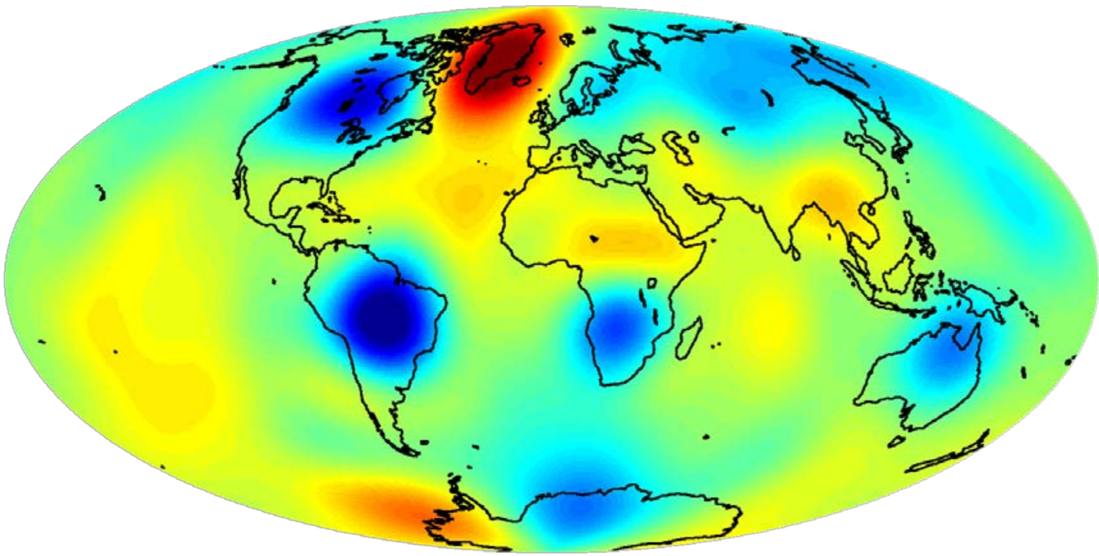
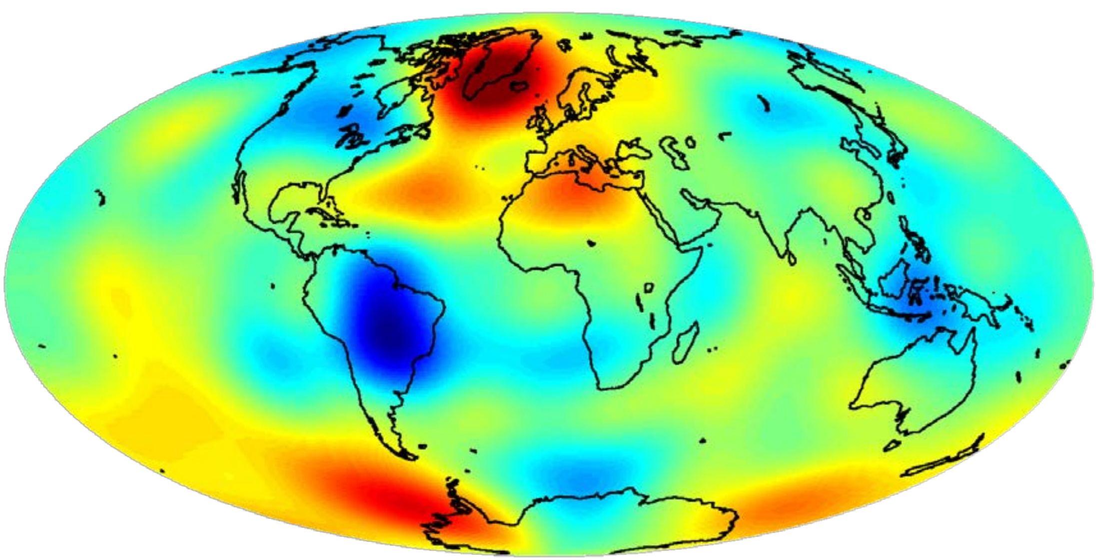
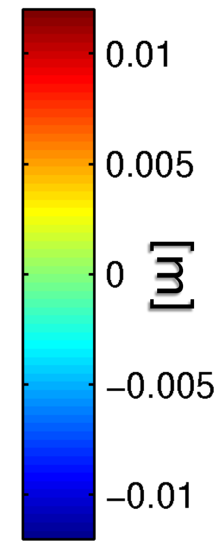


GRACE K-band solution
AIUB-RL02,
March 2011,
up to d/o 10/10
no filtering

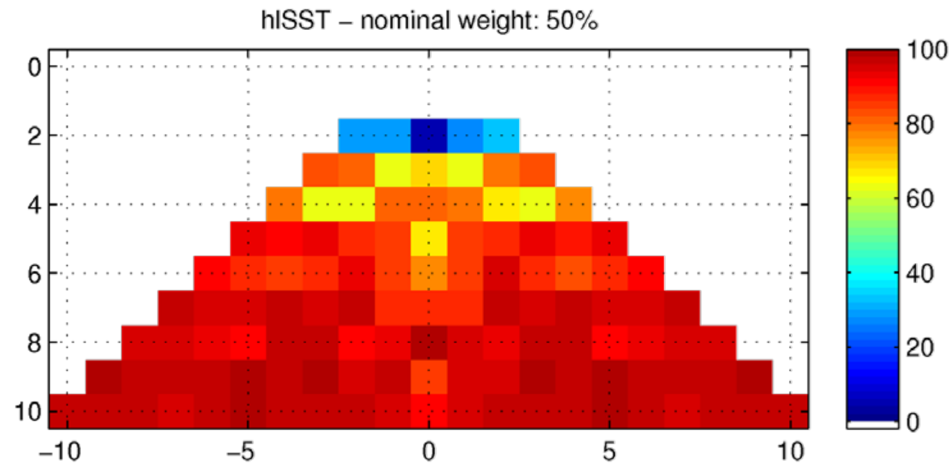


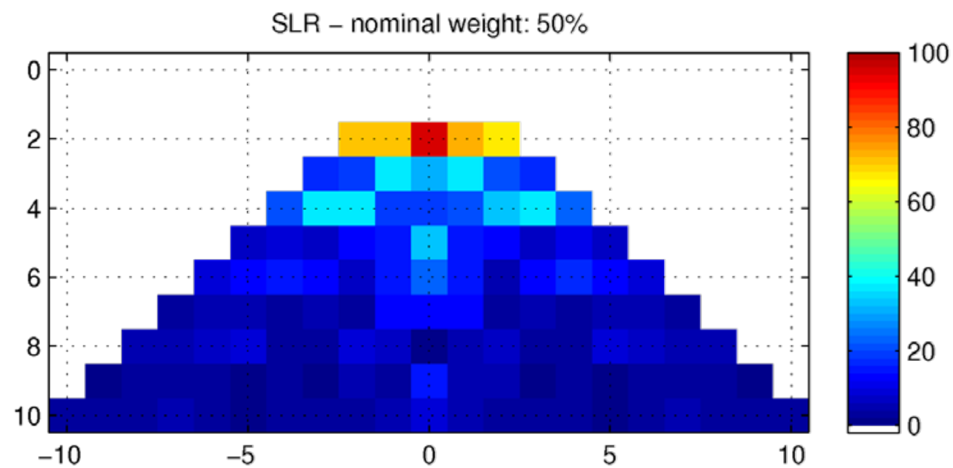
SLR-only solution,
March 2011,
up to d/o 10/10
no filtering



Combined SLR + hl-SST solutions

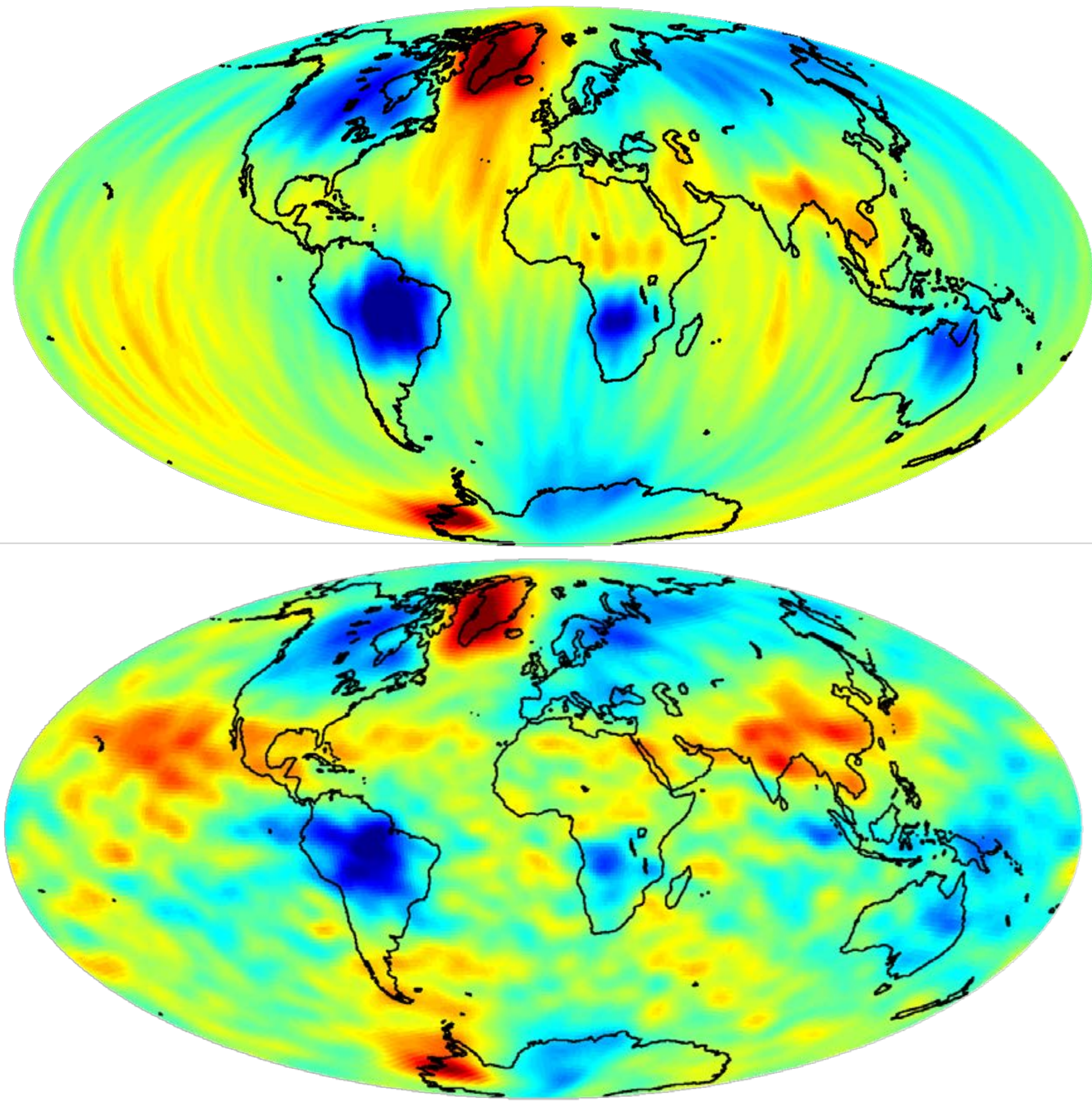
Combination of hlSST and SLR





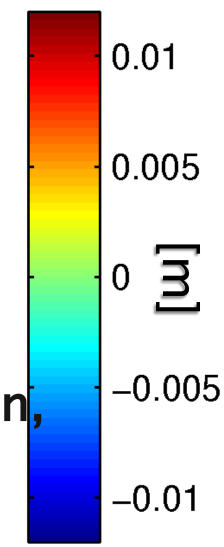
In the combination with hlSST, SLR contributes mostly to degree 2 coefficients, but the relative weighting is still an open issue.

SLR+hl-SST solutions



GRACE K-band solution,
March 2011,
up to d/o 60/60
filtering 300 km

SLR+hl-SST solution,
March 2011,
up to d/o 90/90
filtering 500 km



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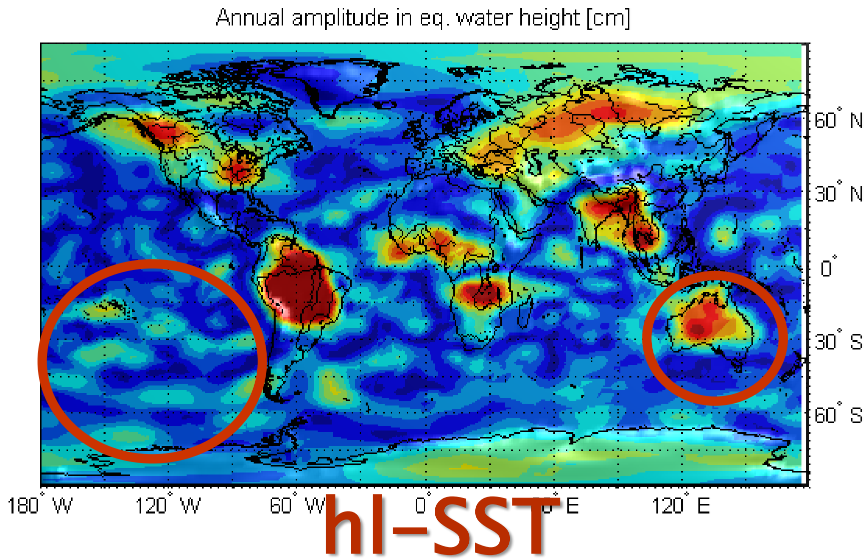
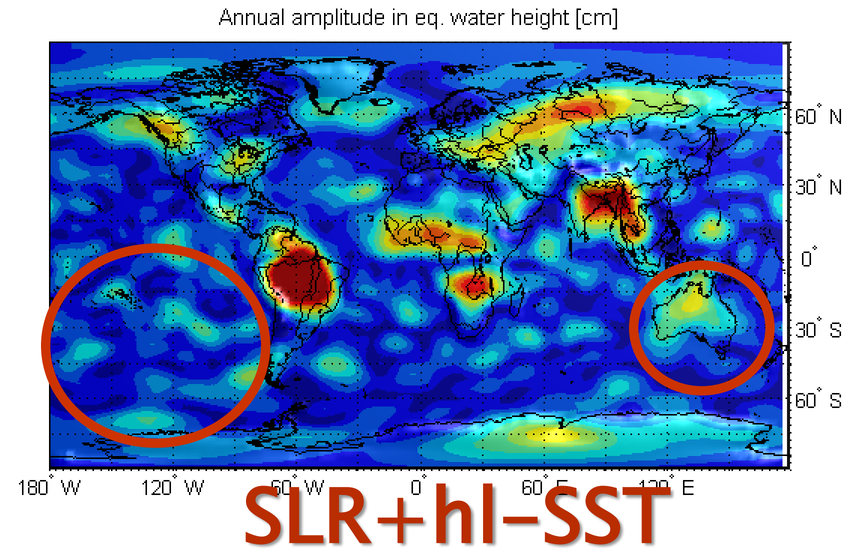
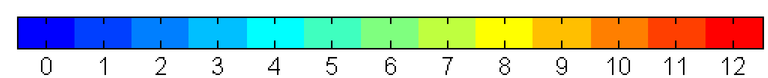
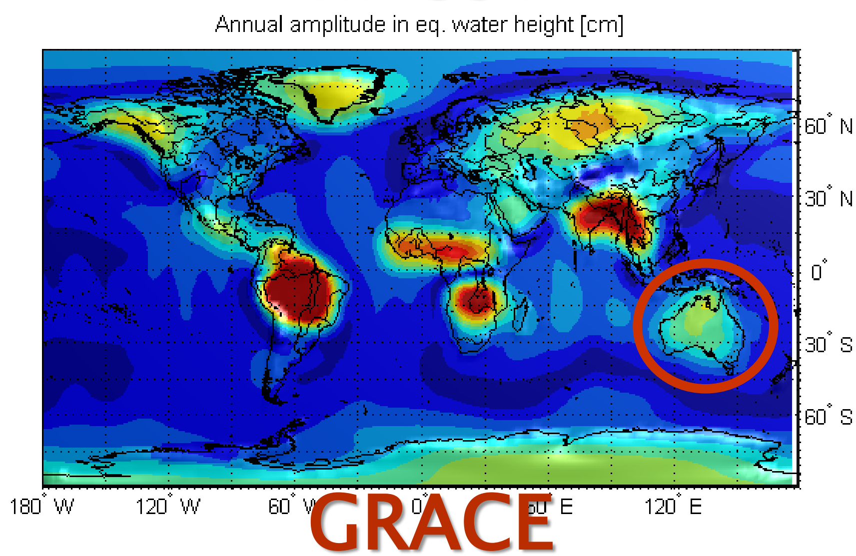
GRACE vs. hl-SST vs. SLR+hl-SST









Combination of hl-SST solutions with SLR reduces the variations over oceans and some spurious signals.

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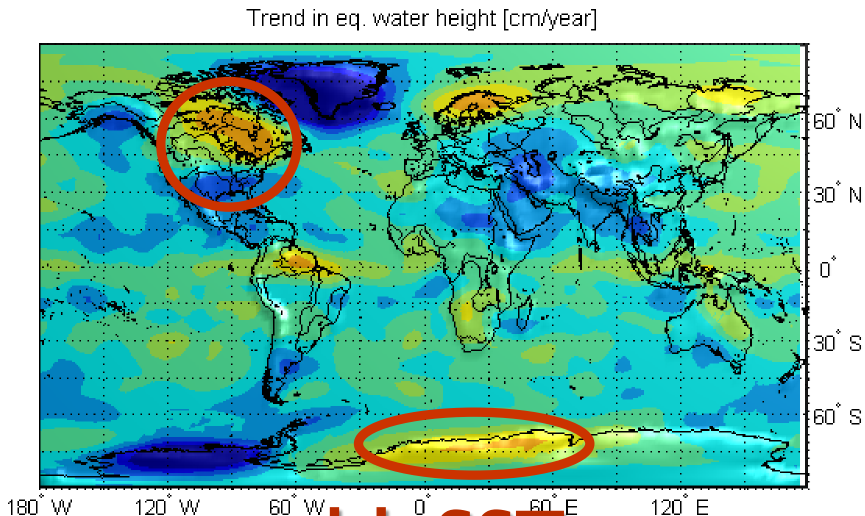
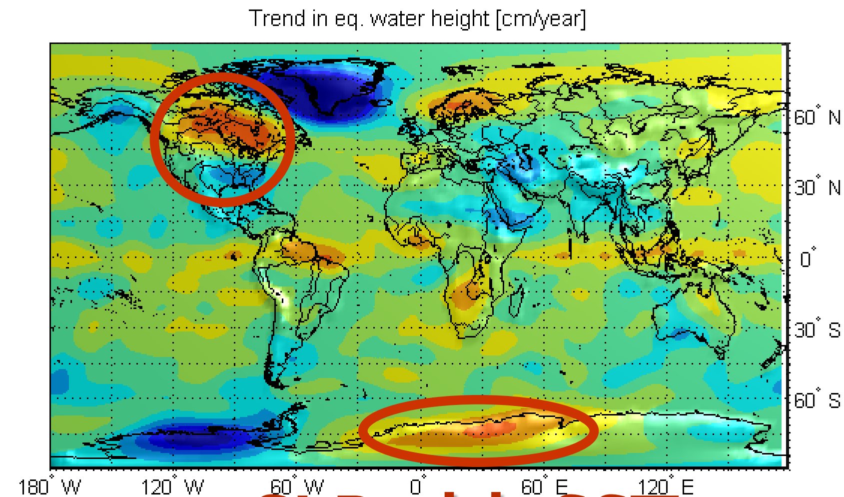
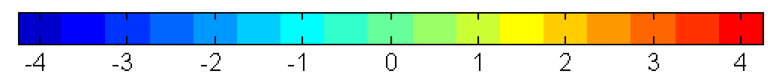
GRACE vs. hl-SST vs. SLR+hl-SST

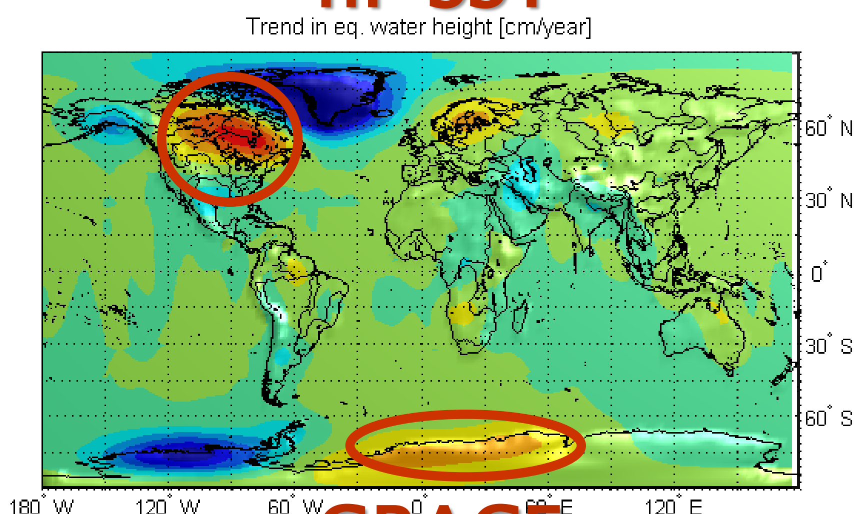


hl-SST



SLR+hl-SST





GRACE

Combination of hl-SST solutions with SLR reduces the variations over oceans and some spurious signals.

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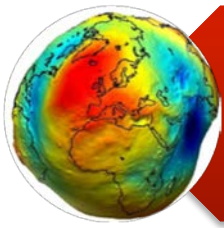
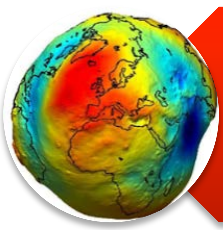
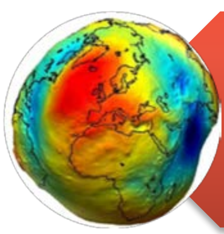
Summary



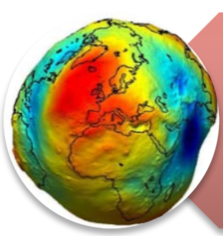
Low degree gravity field parameters can be well derived from SLR observations to geodetic satellites. Low-degree SH provide information about large-scale mass transport in the system Earth.



The mean difference of seasonal signal for low degree SH between SLR-only and GRACE K-band is 7.5E-12, i.e., 23% of mean total annual signal. It implies that the agreement between SLR and GRACE is at 77% level by means of low degree SH.



The combination SLR + hl-SST provides information about mass transport in the system Earth with higher spatial resolution w.r.t. SLR-only solutions.

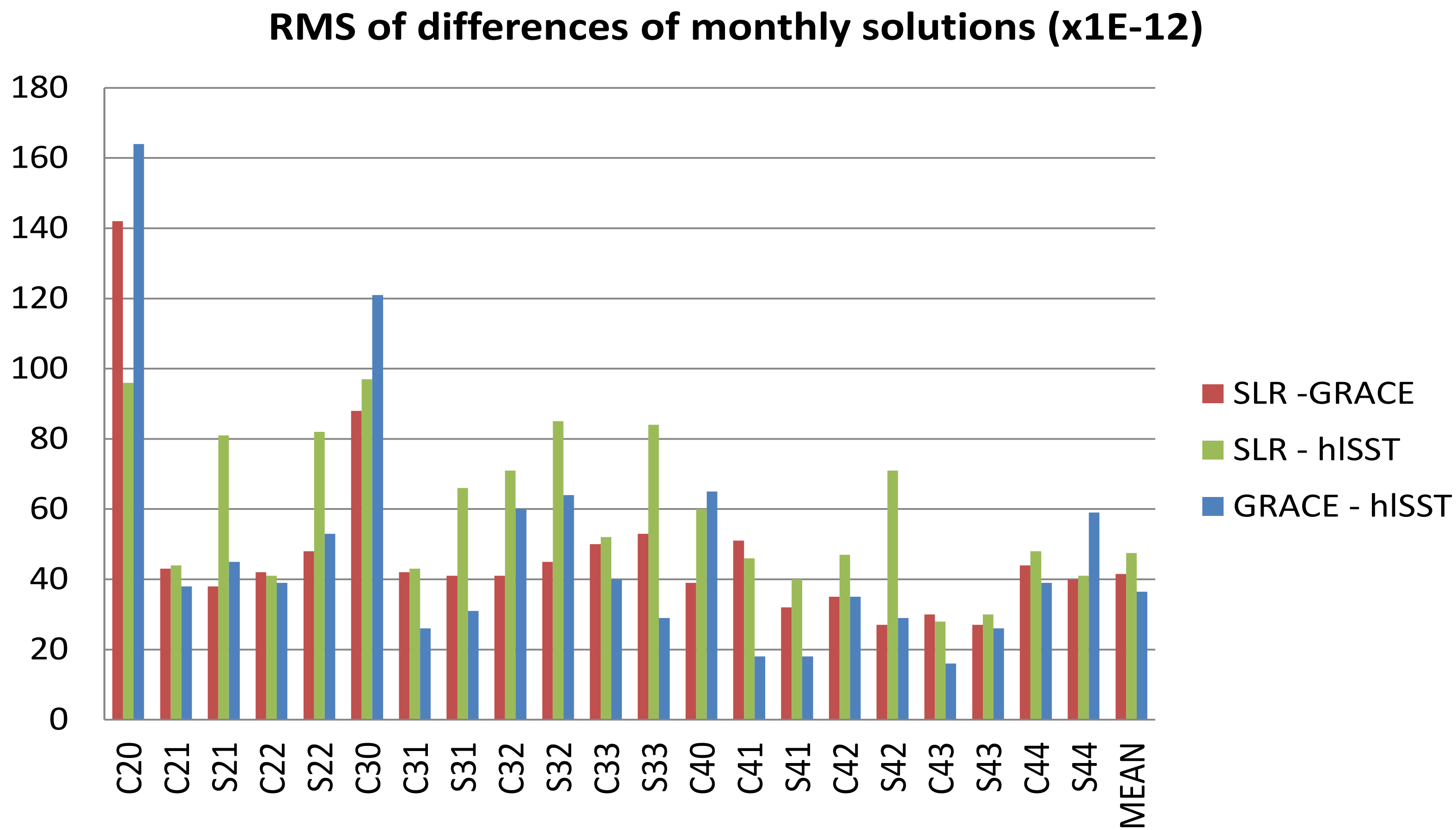


The AIUB SLR-only temporal gravity field solutions will be published soon on ICGEM website.

Thank you
for your attention

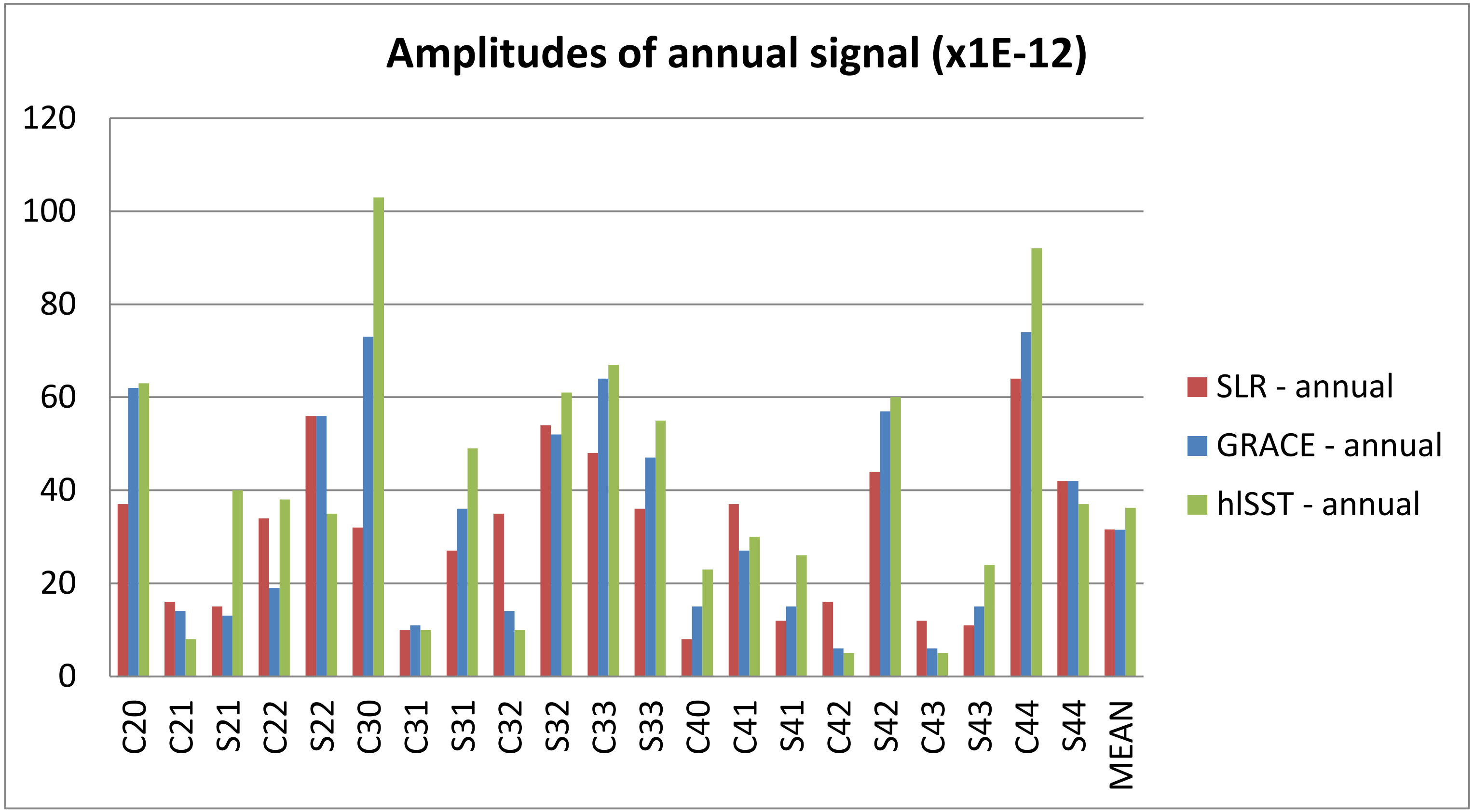
Back-up slides

Comparison of hlSST+SLR w.r.t. GRACE



The mean RMS of differences between estimated SH coefficients are: 41, 47, and 36.E-12 for SLR vs.GRACE, SLR vs.hlSST+SLR, and GRACE vs. hlSST+SLR, respectively.

Comparison of hlSST+SLR w.r.t. GRACE



In hlSST solutions the amplitudes are overestimated by about 12%.

The RMS of differences between estimated amplitudes are 7.5, 9.0, and 13.9E-12 for SLR-GRACE, SLR-hlSST, and GRACE-hlSST, respectively.

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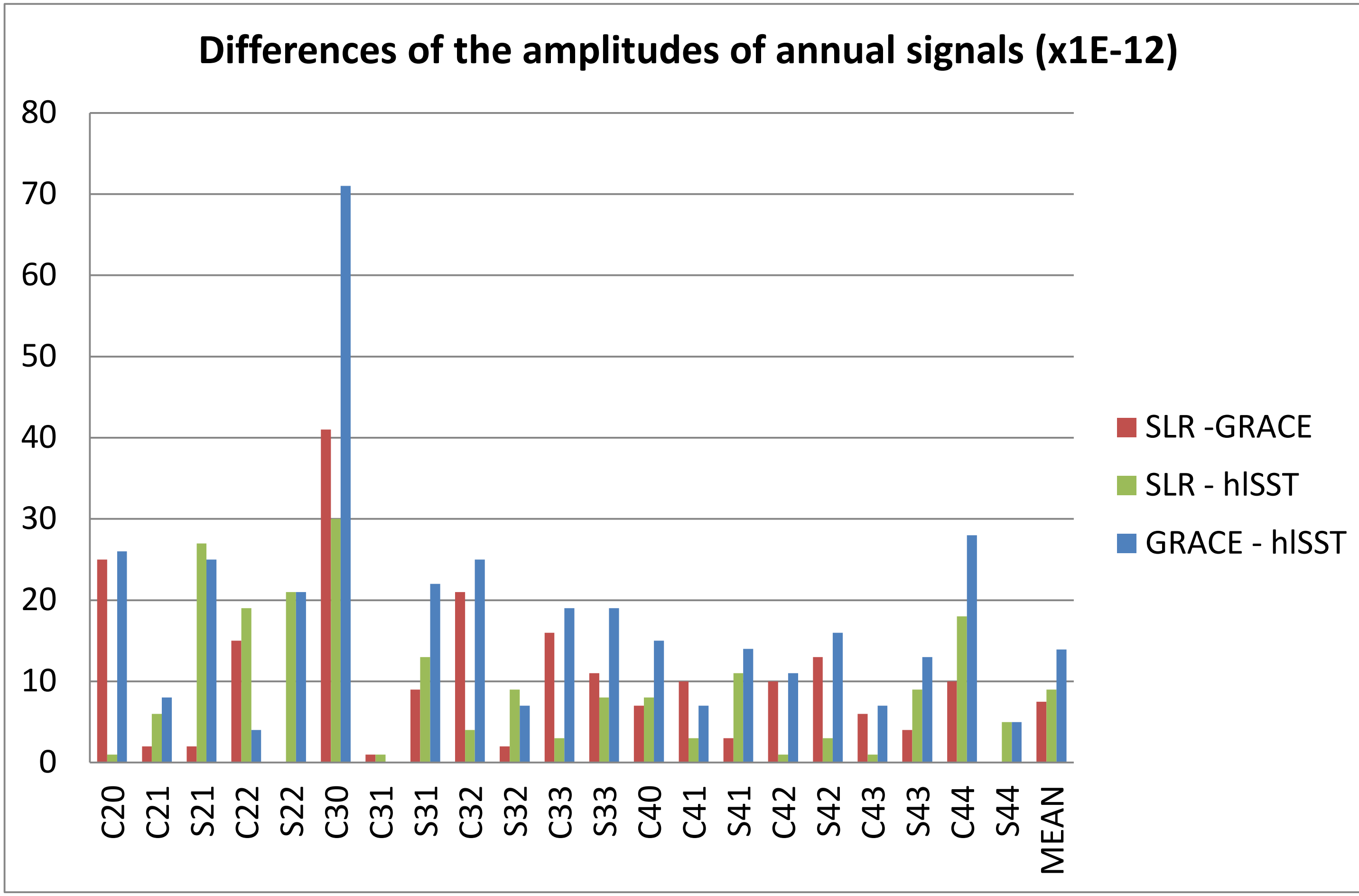
Comparison of hlSST+SLR w.r.t. GRACE



hlSST denotes hlSST+SLR

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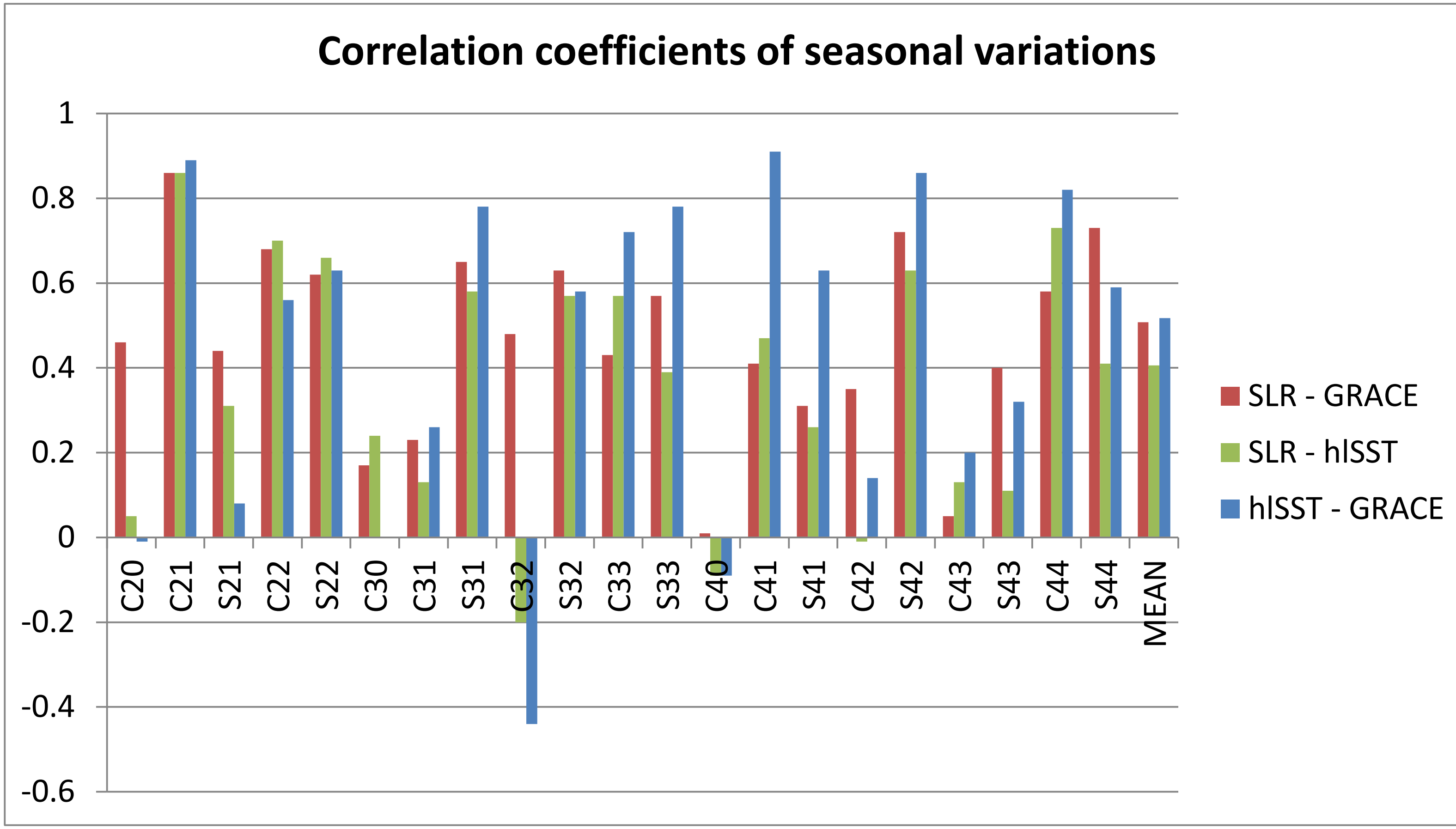
Comparison of hlSST+SLR w.r.t. GRACE



hlSST denotes hlSST+SLR

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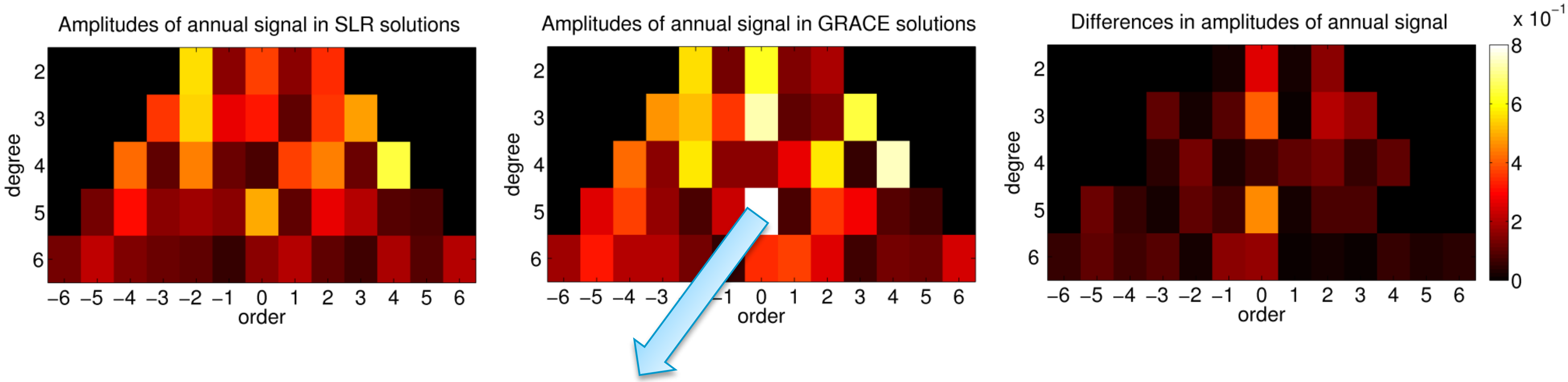
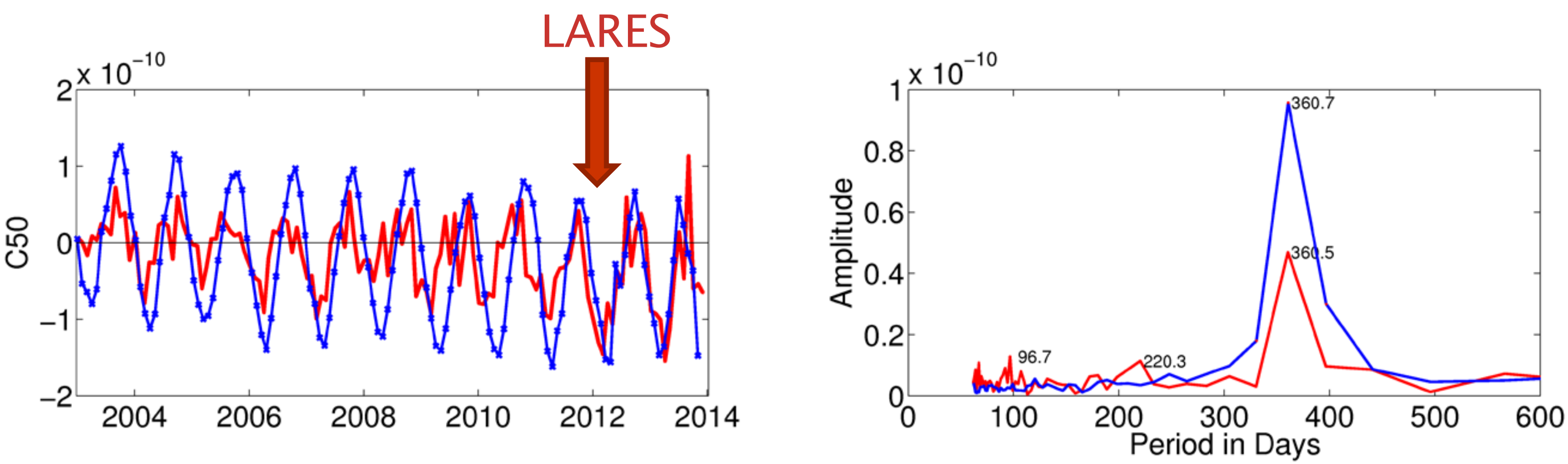
Comparison of SLR w.r.t. GRACE





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Comparison of hlSST+SLR w.r.t. GRACE

Amplitudes of annual signal (x1E-12)		
	Mean (up to d/o 4/4)	Mean without zonals
SLR	30.8	31.5
GRACE	34.2	31.6
hlSST+SLR	40.0	36.2
Mean differences of annual amplitudes (x1E-12)		
SLR – GRACE	9.9	7.5
SLR – hlSST+SLR	9.6	9.0
GRACE – hlSST+SLR	17.3	13.9
Mean correlation coefficients		
SLR – GRACE	0.47	0.51
SLR – hlSST+SLR	0.36	0.41
GRACE – hlSST+SLR	0.44	0.52
RMS of differences (x1E-12)		
SLR – GRACE	42	41
SLR – hlSST+SLR	52	47
GRACE – hlSST+SLR	39	36

SLR Satellite Sensitivity to Gravity Field

Perturbing accel.	Accel. on LAGEOS	Accel. on AJISAI	Accel. on LARES	Accel. on Stella
Gravitational perturbations:				
· Earth's monopole	2.7	6.4	6.5	7.7
· Earth's oblateness $C_{2\,0}$	$1.0 \cdot 10^{-3}$	$6.2 \cdot 10^{-3}$	$6.3 \cdot 10^{-3}$	$8.8 \cdot 10^{-3}$
· Low-order grav. $C_{2\,2}$	$6.0 \cdot 10^{-6}$	$3.6 \cdot 10^{-5}$	$3.7 \cdot 10^{-5}$	$5.1 \cdot 10^{-5}$
· Low-order grav. $C_{6\,6}$	$8.6 \cdot 10^{-8}$	$3.1 \cdot 10^{-6}$	$3.2 \cdot 10^{-6}$	$6.3 \cdot 10^{-6}$
· Mid-order grav. $C_{20\,20}$	$8.1 \cdot 10^{-13}$	$1.5 \cdot 10^{-8}$	$1.6 \cdot 10^{-8}$	$1.1 \cdot 10^{-7}$
· Grav. attr. of Moon	$2.1 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$	$1.3 \cdot 10^{-6}$
· Grav. attr. of Sun	$9.6 \cdot 10^{-7}$	$6.4 \cdot 10^{-7}$	$6.5 \cdot 10^{-7}$	$5.7 \cdot 10^{-7}$
· Grav. attr. of Venus	$1.3 \cdot 10^{-10}$	$8.5 \cdot 10^{-11}$	$8.5 \cdot 10^{-11}$	$7.8 \cdot 10^{-11}$
· Solid Earth tides	$3.7 \cdot 10^{-6}$	$2.0 \cdot 10^{-5}$	$2.0 \cdot 10^{-5}$	$2.9 \cdot 10^{-5}$
· Ocean tides	$3.7 \cdot 10^{-7}$	$1.9 \cdot 10^{-6}$	$2.0 \cdot 10^{-6}$	$3.0 \cdot 10^{-6}$
General relativity:				
· Schwarzschild effect	$2.8 \cdot 10^{-9}$	$1.1 \cdot 10^{-8}$	$1.1 \cdot 10^{-8}$	$1.4 \cdot 10^{-8}$
· Lense-Thirring effect	$2.7 \cdot 10^{-11}$	$1.3 \cdot 10^{-10}$	$1.4 \cdot 10^{-10}$	$1.8 \cdot 10^{-10}$
· Geodetic precession	$3.4 \cdot 10^{-11}$	$4.2 \cdot 10^{-11}$	$4.2 \cdot 10^{-11}$	$4.3 \cdot 10^{-11}$
Non-gravitational perturbations:				
· Solar radiation pressure	$3.5 \cdot 10^{-9}$	$2.5 \cdot 10^{-8}$	$1.1 \cdot 10^{-9}$	$4.4 \cdot 10^{-9}$
· Earth radiation pressure	$4.4 \cdot 10^{-10}$	$8.6 \cdot 10^{-9}$	$3.9 \cdot 10^{-10}$	$1.8 \cdot 10^{-9}$
· Thermal re-radiation	$5.0 \cdot 10^{-11}$	$4.1 \cdot 10^{-10}$	$1.9 \cdot 10^{-11}$	$6.9 \cdot 10^{-11}$
· Light aberration	$1.1 \cdot 10^{-13}$	$1.1 \cdot 10^{-12}$	$5.1 \cdot 10^{-14}$	$2.0 \cdot 10^{-13}$
· Atmospheric drag ($\sim$ min)	$0.8 \cdot 10^{-14}$	$3.0 \cdot 10^{-11}$	$2.6 \cdot 10^{-12}$	$5.0 \cdot 10^{-11}$
· Atmospheric drag ($\sim$ max)	$2.0 \cdot 10^{-13}$	$5.9 \cdot 10^{-10}$	$4.8 \cdot 10^{-11}$	$5.0 \cdot 10^{-8}$

Sośnica et al.: Time varying gravity from SLR and combined SLR and high-low satellite-to-satellite tracking data. GRACE Science Team Meeting 2014, Potsdam, Germany

AJISAI:

- Diameter: 2.15 m
- Mass: 685 kg
- Area-to-mass: A/m: $58 \cdot 10^{-4}$ $m^2\,kg^{-1}$

LAGEOS:

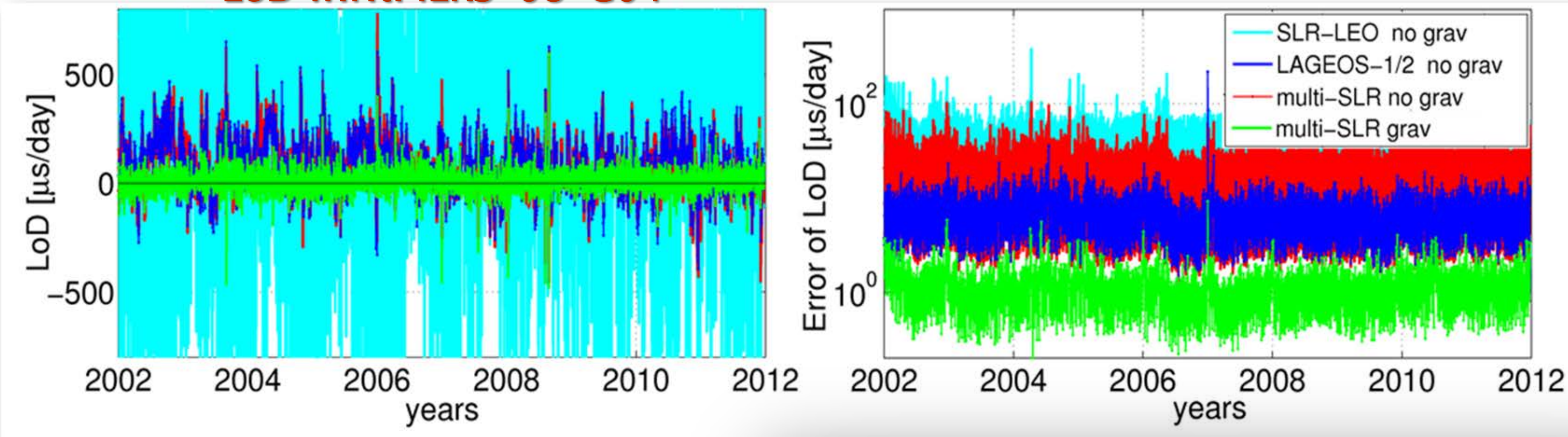
- Diameter: 0.60 m
- Mass: 407 kg
- Area-to-mass: A/m: $6.9 \cdot 10^{-4}$ $m^2\,kg^{-1}$

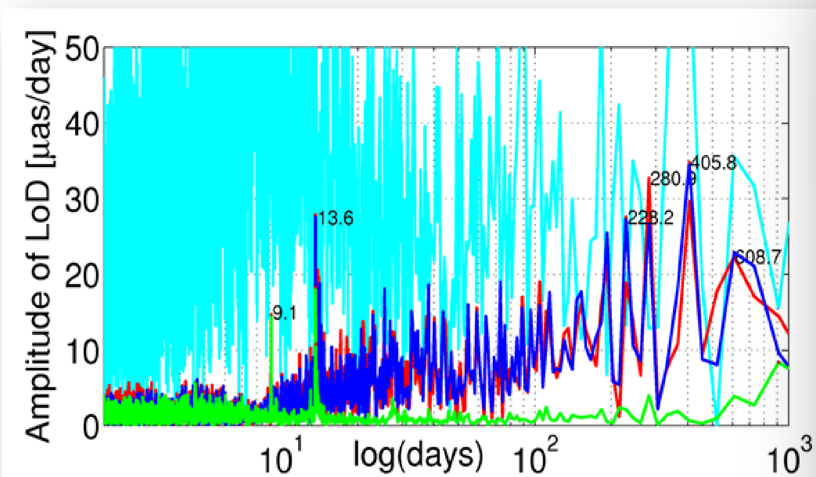
LARES:

- Diameter: 0.36 m
- Mass: 387 kg
- Area-to-mass: A/m: $2.7 \cdot 10^{-4}$ $m^2\,kg^{-1}$

SLR solution with and without estimating gravity field

LoD w.r.t. IERS-08-C04





For LoD, the simultaneous estimation of the gravity field parameters:

- 1. reduces the offset of LoD estimates,
- 2. substantially reduces the a posteriori error of estimated LoD. The mean a posteriori error of LoD is 1.3, 16.9, 7.1, and 44.6 µs/day in the multi-SLR solution with gravity, multi-SLR solution without gravity, LAGEOS-1/2 solution without gravity, and SLR-LEO solution without gravity field parameters, respectively.
- 2. reduces peaks in the spectral analysis, which correspond, e.g., to orbit modeling deficiencies (peaks of 222 days, i.e., draconitic year of LAGEOS-2, 280 days, i.e., eclipsing period of LAGEOS-1),

Estimated parameters of SLR satellites

Satellite	Nominal CoM [mm]	Estimated CoM [mm]	Error [mm]
Starlette	75	77.8	3.1
Stella	75	77.8	3.1
Blits	-209.6	-205.7	8.5
Larets	56.2	63.1	5.5
LARES	133	133.6	2.1
Beacon-C	no data	276.5	4.8
Beacon-C (N hemisphere)	no data	285.1	4.9
Beacon-C (S hemisphere)	no data	220.7	6.7

Due to the lack of information about the parameters of Beacon-C, the center-of-mass corrections had to be estimated on a basis of in-orbit analysis. A significant difference was found in CoM for SLR stations located in Southern and Northern hemispheres.
Estimated area-to-mass for Beacon-C: $A/m = 1.75 \pm 0.2 \cdot 10^{-2}\ m^2\ kg^{-1}$

For Larets, a significant difference w.r.t. nominal CoM was found.